

Squark & Gluino Production at the LHC with NLO Electroweak Contributions

Maïke Trenkel

University of Wisconsin, Madison

Brookhaven Forum 2010

May 27, 2010

in collaboration with

Jan Germer, Wolfgang Hollik, Edoardo Mirabella
Max Planck Institute for Physics, Munich

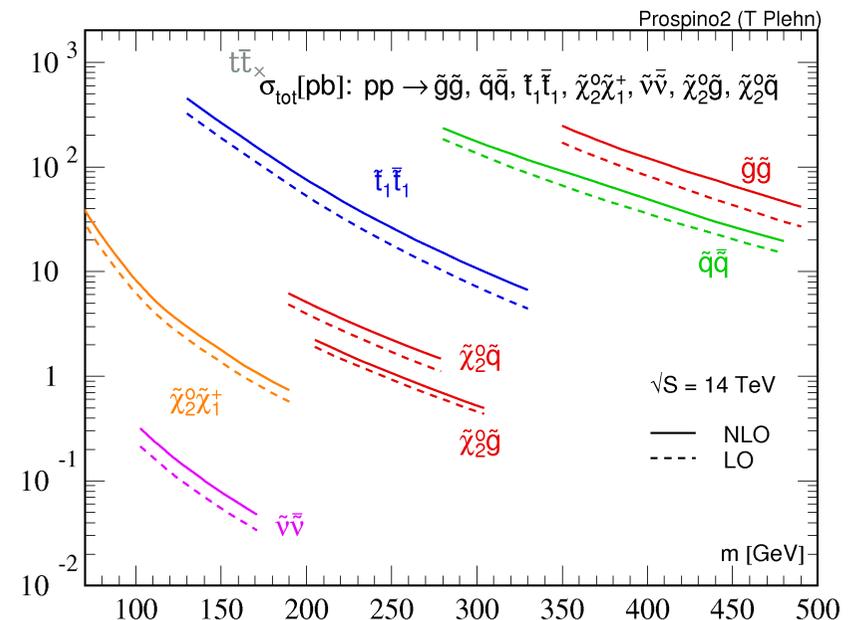
Outline

- **Motivation**
- **Production of Squarks and Gluinos**
 - classification of processes
 - QCD and EW contributions
- **Tree-level and NLO electroweak contributions**
 - handling singularities at NLO EW
 - numerical results for $\tilde{q}\tilde{q}$ production
- **Summary**

Motivation

Why studying production of **squarks and gluinos** at the LHC?

- pair production of color-charged SUSY particles proceeds via **strong interaction**
 - ➔ **large cross sections**
- large top-Yukawa coupling: **top-squark \tilde{t}_1** candidate for **lightest squark**
 - ➔ **high production rates**
- **cross section depend** essentially **on final state masses**
 - ➔ bounds on cross section allow for lower mass bounds without specifying all other SUSY parameters

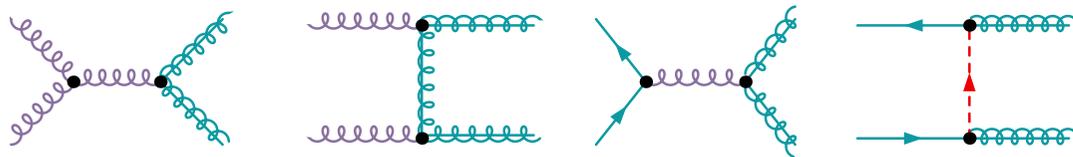


Overview: Squark & Gluino Production at LO

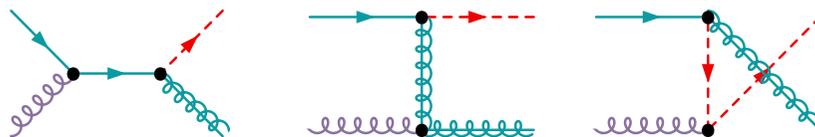
Squark and gluino production at LO is well known since many years

[Kane & Leveille '82, Harrison & Llewellyn Smith '83, Reya & Roy '85, Dawson, Eichten, Quigg '85, Baer & Tata '85]

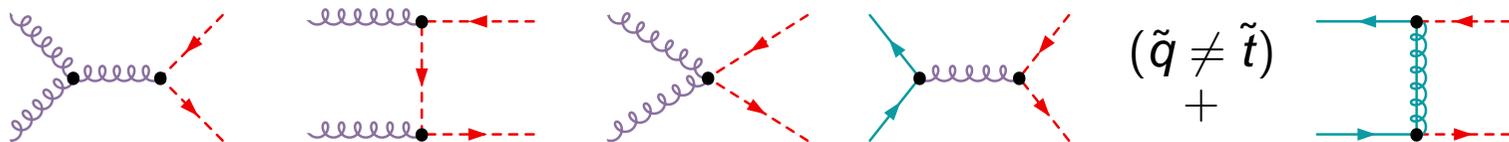
- $\mathcal{O}(\alpha_s^2)$: – $\tilde{g}\tilde{g}$ production



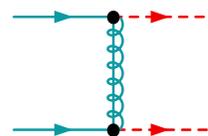
- $\tilde{g}\tilde{q}$ production



- $\tilde{q}\tilde{q}^*, \tilde{t}\tilde{t}^*$ production



- $\tilde{q}\tilde{q}$ production

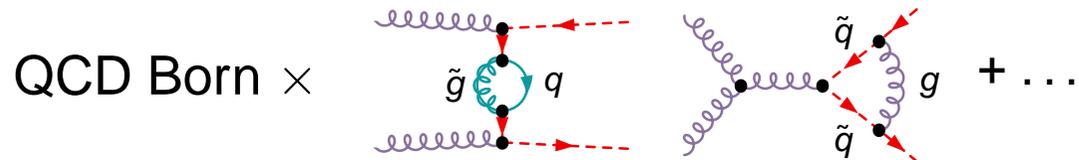


Higher Order Corrections

Important **higher order effects** due to **QCD corrections**:

- $\mathcal{O}(\alpha_s^3)$: QCD NLO corrections

[Beenakker, Höpker, Spira, Zerwas '95 & '97] &
[Beenakker, Krämer, Plehn, Spira, Zerwas '98]
→ PROSPINO



+ real gluon & real quark radiation

- large positive corrections
 - reduced scale dependence
 - negligible in normalized distributions
- beyond NLO QCD: NLL resummation, approximate NNLO QCD

[Kulesza, Motyka '08 & '09], [Langenfeld, Moch '09],
[Beenakker, Breusing, Krämer, Kulesza, Laenen, Niessen '09]

Electroweak Contributions – at tree level

$\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, and $\tilde{q}\tilde{q}$ production also possible by **tree-level EW processes!**

[Bornhauser, Drees, Dreiner, Kim '07]
[Bozzi, Fuks, Herrmann, Klasen '07],[Arhrib, Benbrik, Cheung, Yuan '09]

- $\mathcal{O}(\alpha^2 + \alpha_s\alpha)$: **pure EW tree-level** contributions ($\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{q}$ prod.)

$$\left| \begin{array}{c} \text{Diagram 1: } \gamma, Z \text{ exchange} \\ \text{Diagram 2: } \tilde{\chi}^0 \text{ exchange} \end{array} \right|^2 \quad (\tilde{q} \neq \tilde{t})$$

+ EW-QCD tree-level **interferences** to $\tilde{q}\tilde{q}^{(*)}$ production

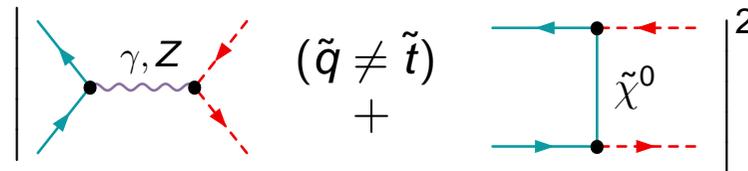
$$\left(\text{Diagram 1: } \gamma, Z \text{ exchange} \right) \times \left(\text{Diagram 2: } \tilde{g} \text{ exchange} \right) + \left(\text{Diagram 3: } \tilde{\chi}^0 \text{ exchange} \right) \times \left(\text{Diagram 4: } g \text{ exchange} \right)$$

Electroweak Contributions – at tree level

$\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, and $\tilde{q}\tilde{q}$ production also possible by **tree-level EW processes!**

[Bornhauser, Drees, Dreiner, Kim '07]
[Bozzi, Fuks, Herrmann, Klasen '07],[Arhrib, Benbrik, Cheung, Yuan '09]

- $\mathcal{O}(\alpha^2 + \alpha_s\alpha)$: **pure EW tree-level** contributions ($\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{q}$ prod.)



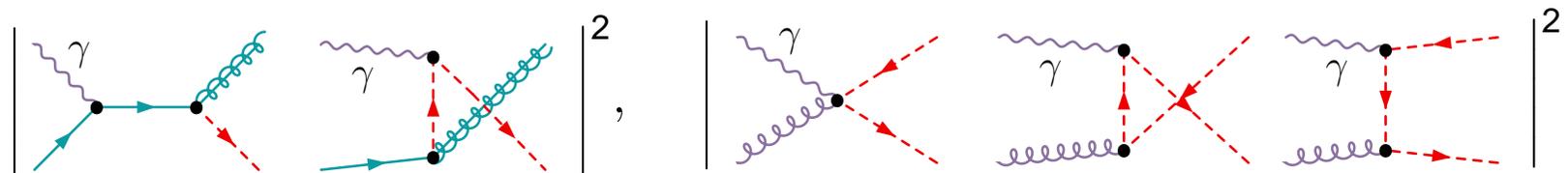
+ EW-QCD tree-level **interferences** to $\tilde{q}\tilde{q}^{(*)}$ production



New production channel for $\tilde{g}\tilde{q}$, $\tilde{t}\tilde{t}^*$, and $\tilde{q}\tilde{q}^*$ production:

[Hollik, Kollar, MT '07], [Hollik, Mirabella '08]
[Hollik, Mirabella, MT '08]

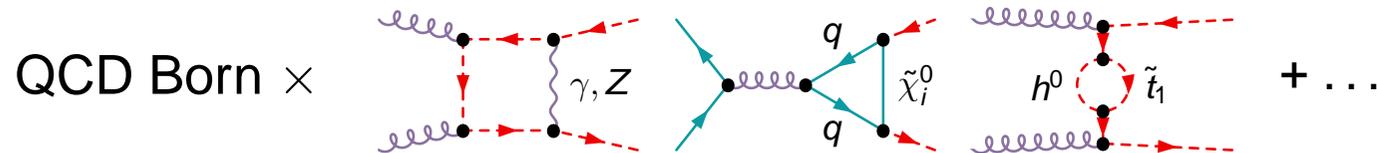
- $\mathcal{O}(\alpha_s\alpha)$: **photon induced processes**



Electroweak Contributions – at one-loop level

- $\mathcal{O}(\alpha_s^2 \alpha)$: NLO EW corrections

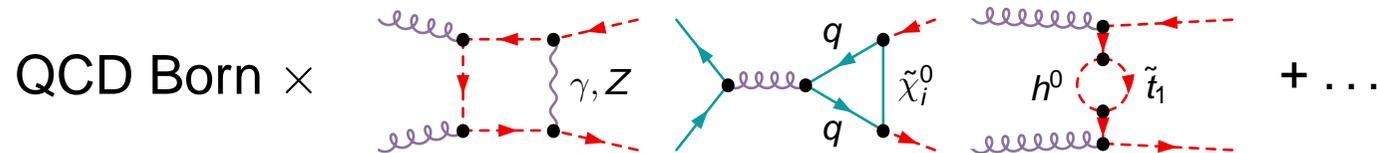
[Hollik, Kollar, MT '07], [Beccaria et. al. '08]
 [Hollik, Mirabella '08], [Hollik, Mirabella, MT '09]
 [Mirabella '09], [Germer, Hollik, Mirabella, MT '10]



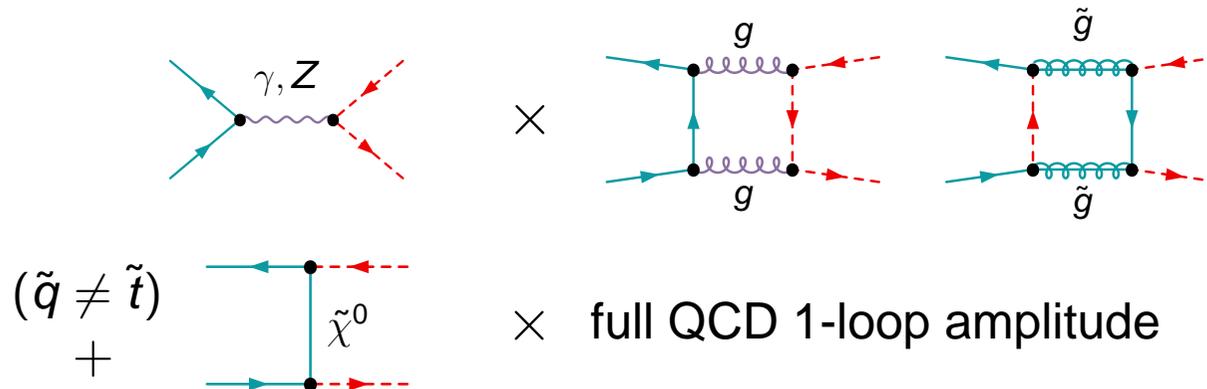
Electroweak Contributions – at one-loop level

- $\mathcal{O}(\alpha_s^2 \alpha)$: NLO EW corrections

[Hollik, Kollar, MT '07], [Beccaria et. al. '08]
 [Hollik, Mirabella '08], [Hollik, Mirabella, MT '09]
 [Mirabella '09], [Germer, Hollik, Mirabella, MT '10]



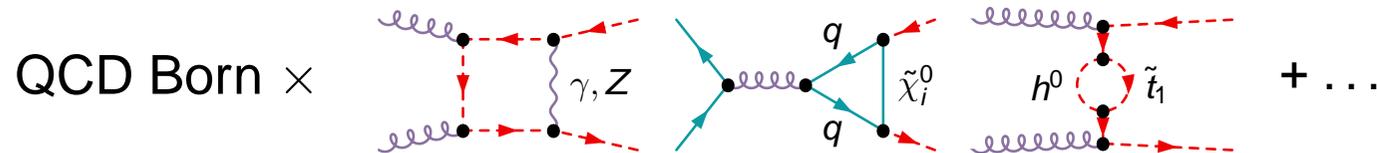
- + EW-QCD one-loop interferences for $\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^{(*)}$ production



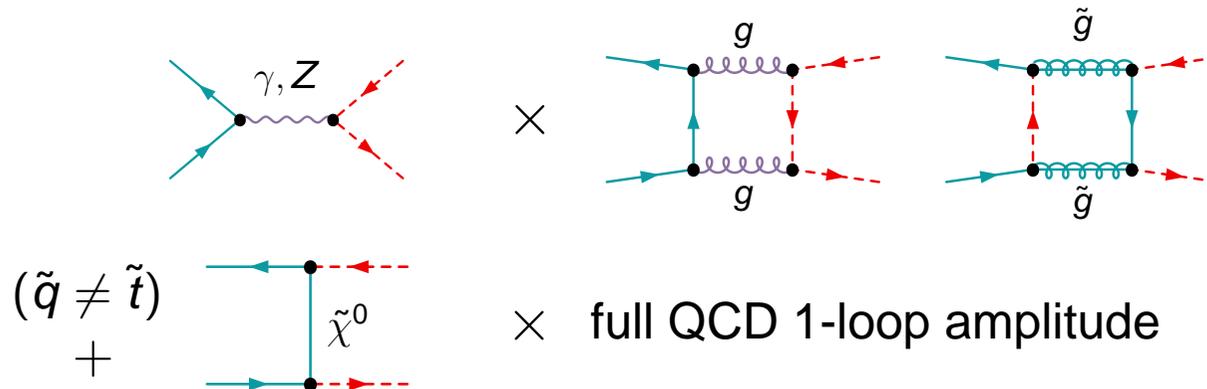
Electroweak Contributions – at one-loop level

- $\mathcal{O}(\alpha_s^2 \alpha)$: NLO EW corrections

[Hollik, Kollar, MT '07], [Beccaria et. al. '08]
 [Hollik, Mirabella '08], [Hollik, Mirabella, MT '09]
 [Mirabella '09], [Germer, Hollik, Mirabella, MT '10]



- + EW-QCD one-loop interferences for $\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^{(*)}$ production



- + real photon, gluon, and quark radiation

NLO EW Corrections: Singularities at $\mathcal{O}(\alpha_s^2\alpha)$

We use **FeynArts & FormCalc** to automatize the calculation.
Process-dependent solutions are necessary in singular regions:

- **UV singularities** (self energies, vertices) from **loop integrals**

→ **renormalization** required

$[\tilde{t}\tilde{t}^*, \tilde{g}\tilde{q}, \tilde{g}\tilde{g}]$: on-shell renorm. of quarks & squarks at $\mathcal{O}(\alpha)$;

$\tilde{q}\tilde{q}^{(*)}$: full QCD 1-loop amplitude enters, full $\mathcal{O}(\alpha_s)$ renorm. required]

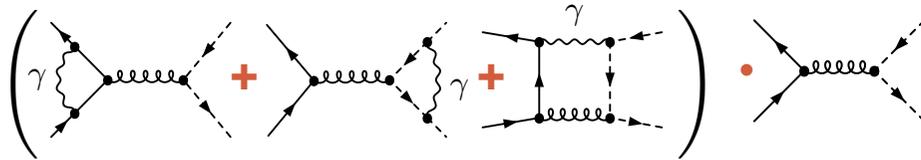
NLO EW Corrections: Singularities at $\mathcal{O}(\alpha_s^2\alpha)$

We use **FeynArts & FormCalc** to automatize the calculation.
Process-dependent solutions are necessary in singular regions:

- **UV singularities** (self energies, vertices) from **loop integrals**
 - ➔ **renormalization** required
 - $[\tilde{t}\tilde{t}^*, \tilde{g}\tilde{q}, \tilde{g}\tilde{g}$: on-shell renorm. of quarks & squarks at $\mathcal{O}(\alpha)$;
 $\tilde{q}\tilde{q}^{(*)}$: full QCD 1-loop amplitude enters, full $\mathcal{O}(\alpha_s)$ renorm. required]
- **IR soft singularities** from $m_\gamma = m_g = 0$
 - ➔ real **photon** and **gluon bremsstrahlung**
 - [technical: mass regularization + phase space slicing/ dipole subtraction]
- **IR collinear singularities** from $m_q = 0$
 - ➔ real photon and gluon bremsstrahlung
 - ➔ factorization and **redefinition of PDFs** at $\mathcal{O}(\alpha)$ or $\mathcal{O}(\alpha_s)$

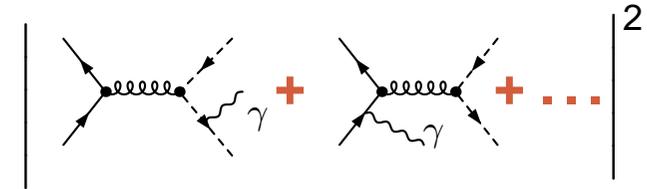
How to obtain an IR-finite cross section for $q\bar{q} \rightarrow \tilde{t}\tilde{t}^*$

- soft divergent diagrams

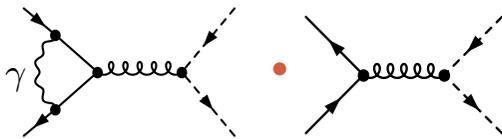


and

- soft photon bremsstrahlung

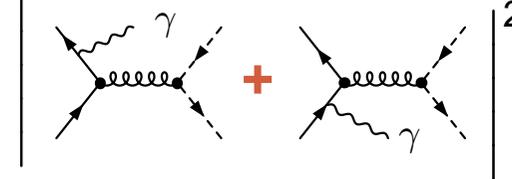


- collinear divergent diagram



and

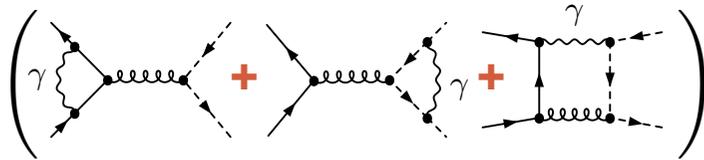
- hard, collinear γ bremsstrahlung



+ redefinition of PDFs at $\mathcal{O}(\alpha)$: subtract $\ln(m_q^2)$ -terms from $\sigma_{q\bar{q}}$

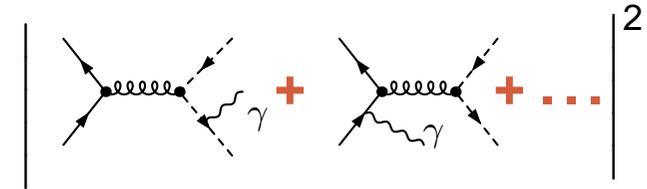
How to obtain an IR-finite cross section for $q\bar{q} \rightarrow \tilde{t}\tilde{t}^*$

- soft divergent diagrams

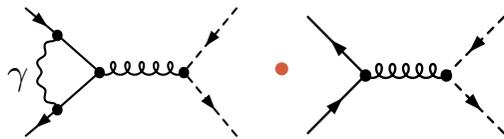


and

- soft photon bremsstrahlung

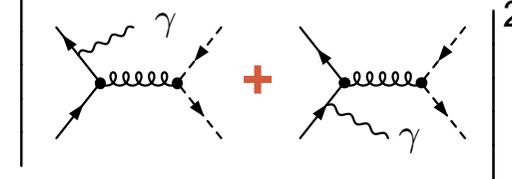


- collinear divergent diagram



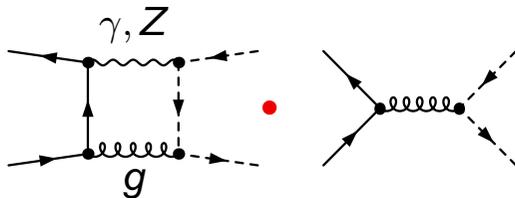
and

- hard, collinear γ bremsstrahlung



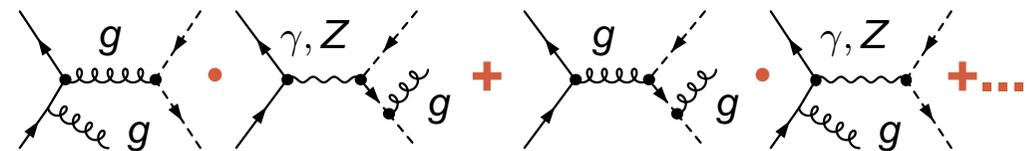
+ redefinition of PDFs at $\mathcal{O}(\alpha)$: subtract $\ln(m_q^2)$ -terms from $\sigma_{q\bar{q}}$

- soft gluon divergent diagrams

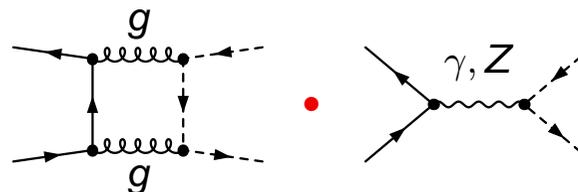


and

- soft gluon bremsstrahlung



- interference of QCD boxes and EW Born



$\tilde{q}\tilde{q}$ production: Overview

- distinguish 36 channels for squarks of different flavor or chirality:

	Class	QCD diagram(s)	EW diagram(s)
$\tilde{u}\tilde{u}, \tilde{d}\tilde{d},$ $\tilde{c}\tilde{c}, \tilde{s}\tilde{s}$	PP $\rightarrow \tilde{q}_\alpha \tilde{q}_\beta$ same flavor		+
$\tilde{u}\tilde{d}, \tilde{c}\tilde{s}$	PP $\rightarrow \tilde{q}_\alpha \tilde{q}'_\beta$ different flavor, same doublet		+
$\tilde{u}\tilde{c}, \tilde{u}\tilde{s},$ $\tilde{d}\tilde{c}, \tilde{d}\tilde{s}$	PP $\rightarrow \tilde{q}_\alpha \tilde{q}'_\beta$ different flavor, different doublet		+

→ manifold **interferences** between QCD & EW diagrams

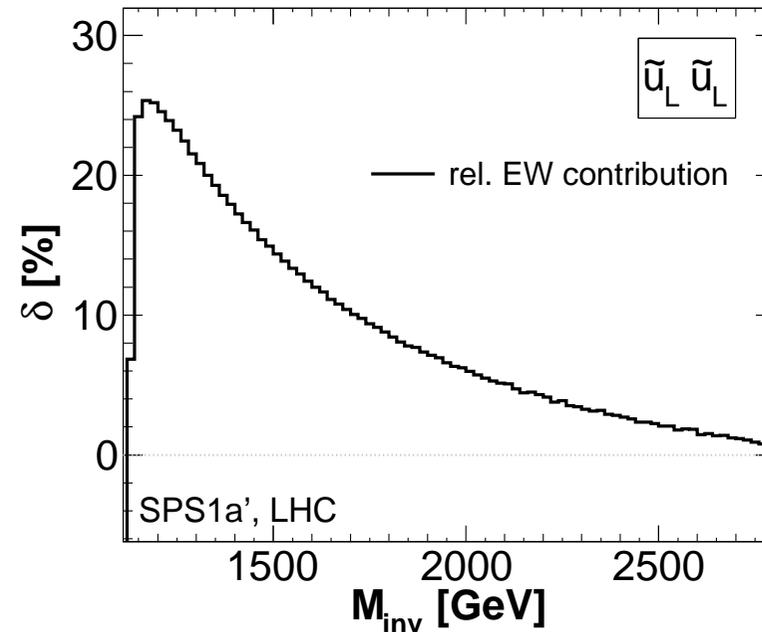
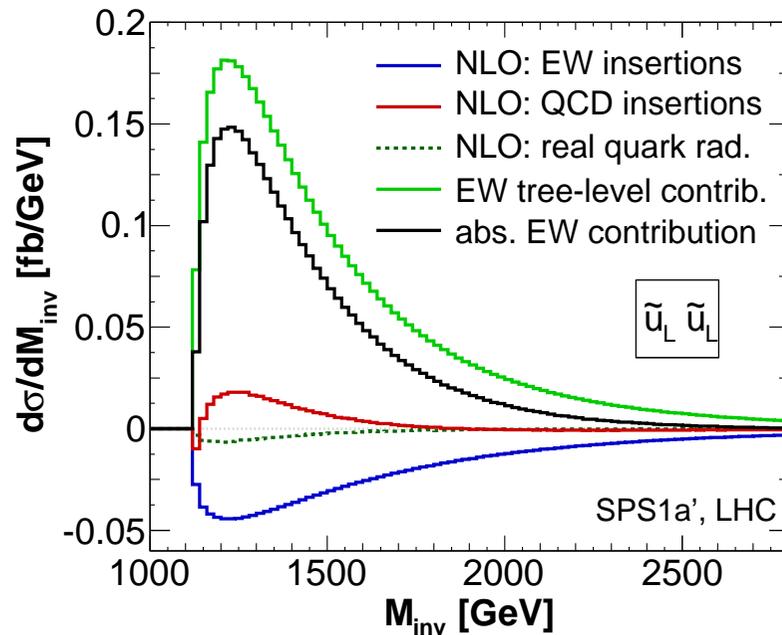
- at tree-level of $\mathcal{O}(\alpha_s \alpha)$ for $\tilde{q}_L \tilde{q}_L$ and $\tilde{q}_R \tilde{q}_R$ production
- at NLO EW of $\mathcal{O}(\alpha_s^2 \alpha)$ for all processes

Numerical Results – $\tilde{q}\tilde{q}$ production

$\tilde{u}\tilde{u}$ prod.:

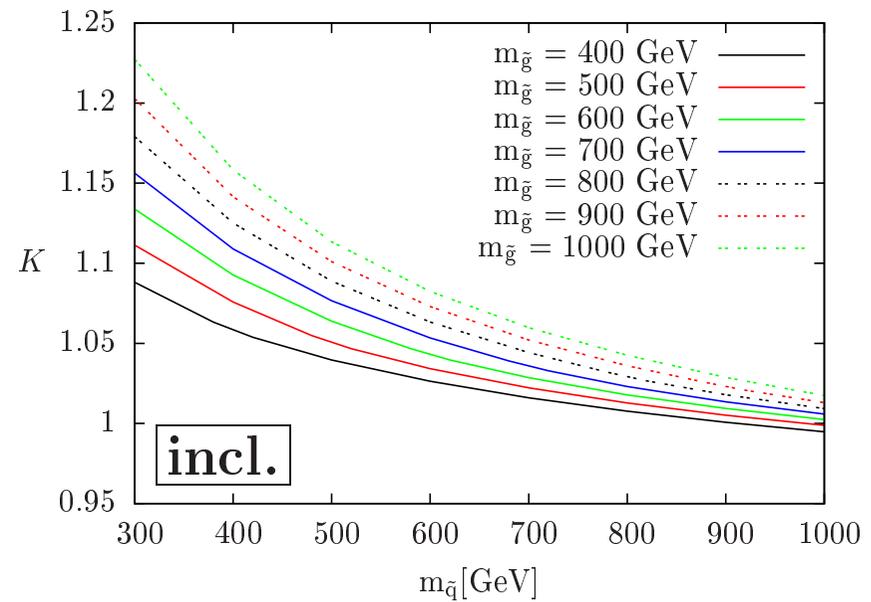
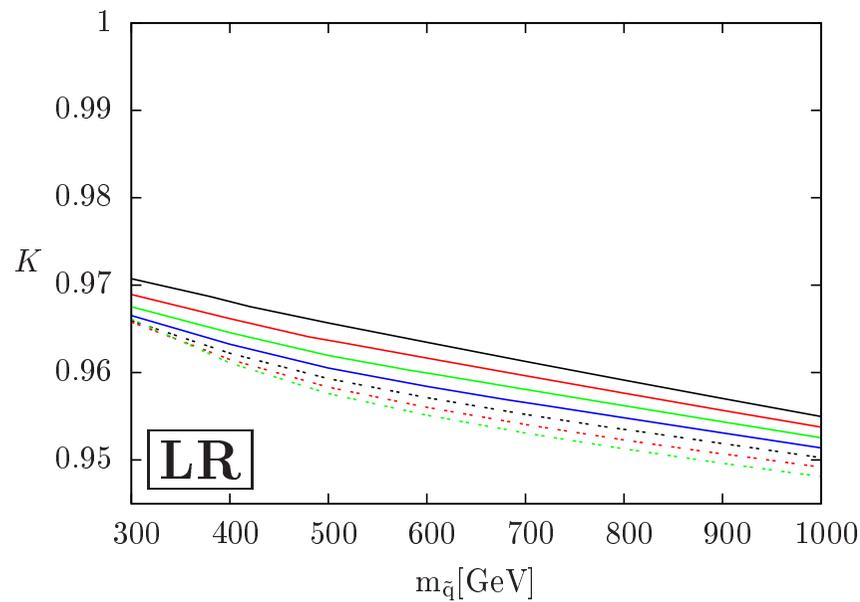
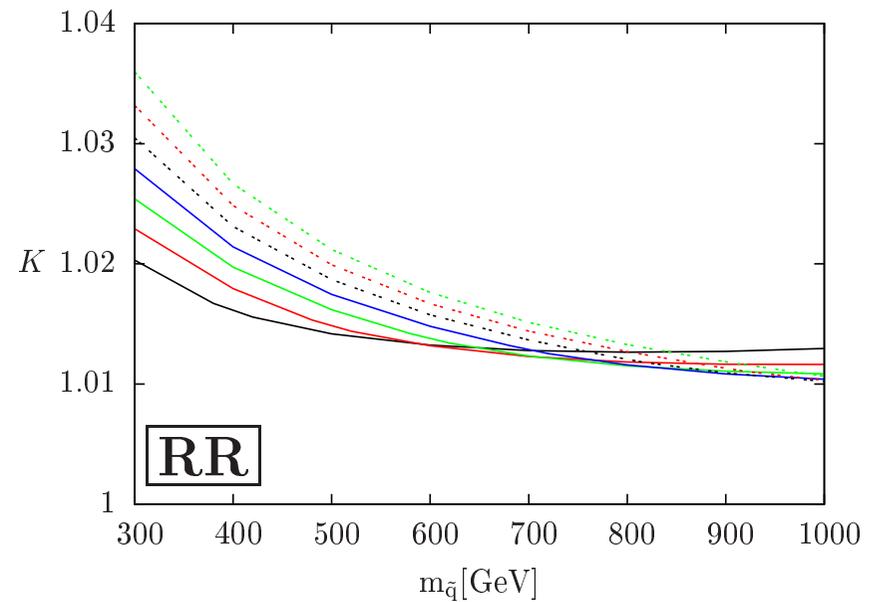
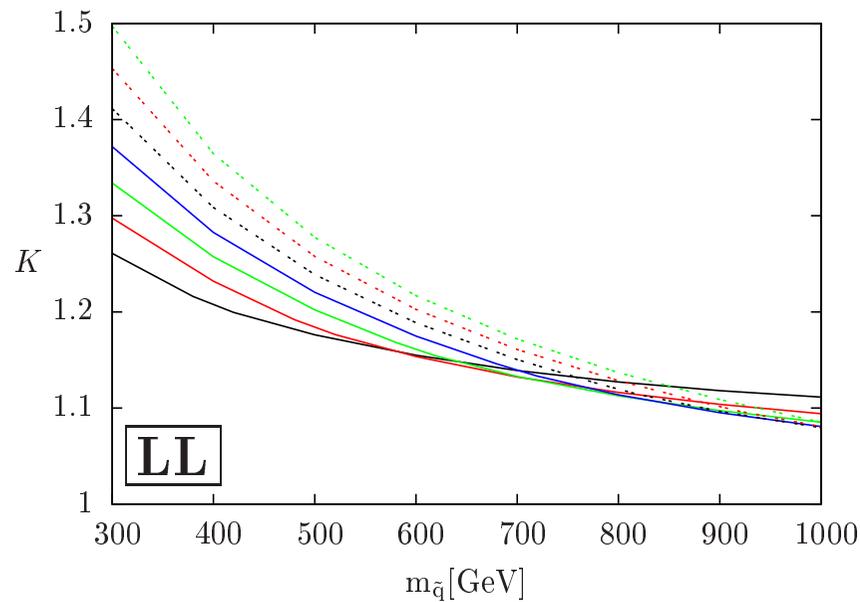
	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g}$ $\mathcal{O}(\alpha_s\alpha)$	$\Delta\sigma^{EW,tree}$ $\mathcal{O}(\alpha^2+\alpha_s\alpha)$	δ
$\tilde{u}_L \tilde{u}_L$	487 fb	-30 fb	-	94 fb	13%
$\tilde{u}_R \tilde{u}_R$	537 fb	-4.5 fb	-	29 fb	4.5 %
$\tilde{u}_L \tilde{u}_R$	630 fb	-26 fb	-	1.3 fb	-4.0 %

$[m(\tilde{u}_L) = 561 \text{ GeV}, m(\tilde{u}_R) = 543 \text{ GeV}, \text{MRST 2004 QED}, 14 \text{ TeV}]$



- many interference contributions! **EW tree-level channels important**
- total EW contributions significant for left-handed squarks

EW Contributions to $\tilde{q}\tilde{q}$ prod.: $K = \sigma^{NLO} / \sigma^{Born}$

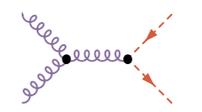
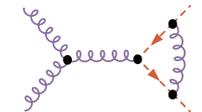
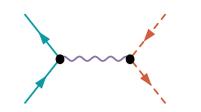
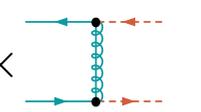
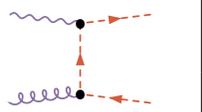
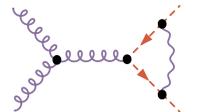


Summary

- Exciting times ahead: SUSY will be probed at the LHC
Squarks and gluinos could be produced at a **very high rate**
- QCD corrections already well known,
NLO EW corrections to $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}^*$, $\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}$ prod. **completed**,
to $\tilde{b}\tilde{b}^*$ production are in preparation
- **EW contributions** have a **rich structure**
 - ➔ strongly **dependent on chirality** of produced particles
 - ➔ non-zero **photon PDF** opens important production channel
 - ➔ **EW tree-level** and involved EW-QCD interference contributions
- **EW contributions** to integrated cross sections are often small,
but become **important in distributions**

Backup

Overview: Squark and Gluino Production @ LHC

	LO	NLO QCD	EW contributions			
	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha_s\alpha)$	$\mathcal{O}(\alpha_s\alpha)$	$\mathcal{O}(\alpha_s^2\alpha)$
$\tilde{g}\tilde{g}$	+	+	-	-	-	+
$\tilde{g}\tilde{q}$	+	+	-	-	+	+
$\tilde{t}\tilde{t}^*$	+	+	+	-	+	+
$\tilde{q}\tilde{q}^*$	+	+	+	+	+	+
$\tilde{q}\tilde{q}$	+	+	+	+	-	+
				\times 		

Integrated Cross Sections in SPS1a'

final state	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g/\gamma q}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW,LO}$ $\mathcal{O}(\alpha^2+\alpha_s\alpha)$	δ
$\tilde{g}\tilde{g}$	6187 fb	-4 fb	—	—	0.07%
$\tilde{g}\tilde{q}_L$	10010 fb	-248 fb	4.9 fb	—	-2.4%
$\tilde{g}\tilde{q}_R$	10820 fb	9.8 fb	5.3 fb	—	0.1%
$\tilde{g}\tilde{q}$	20827 fb	-238 fb	10.2 fb	—	-1.1%
$\tilde{t}_1\tilde{t}_1^*$	2670 fb	-22 fb	38 fb	1.2 fb	0.6%
$\tilde{t}_2\tilde{t}_2^*$	186 fb	-31.6 fb	3.8 fb	0.3 fb	-14.8%
$\tilde{q}_L\tilde{q}_L^*$	1016 fb	-9.9 fb	11 fb	-22 fb	-2.1%
$\tilde{q}_R\tilde{q}_R^*$	1235 fb	-2.1 fb	13 fb	-14 fb	-0.3%
$\tilde{q}\tilde{q}^*$	2251 fb	-12 fb	24 fb	-37 fb	-1.1%
$\tilde{q}_L\tilde{q}_L$	1718 fb	-75 fb	—	379 fb	17.6%
$\tilde{q}_R\tilde{q}_R$	1982 fb	-2 fb	—	32 fb	1.5%
$\tilde{q}_R\tilde{q}_L$	1744 fb	-71 fb	—	3 fb	-3.9%
$\tilde{q}\tilde{q}$	5444 fb	-147 fb	—	413 fb	4.9%

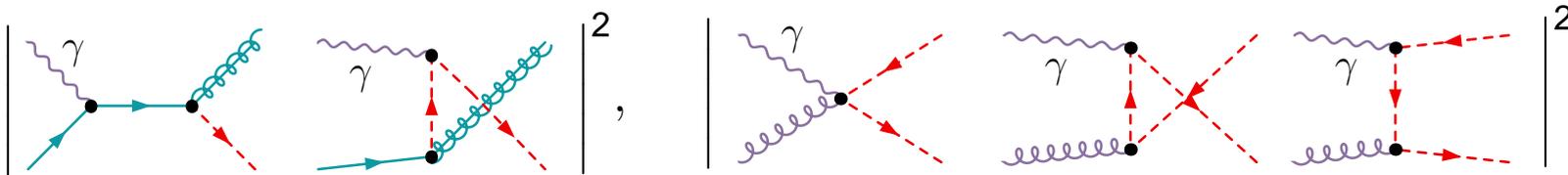
[MRST 2004 QED, 14 TeV, $m_t = 170.9$ GeV; SPS1a' scenario: $m_{\tilde{g}} = 609$ GeV, $m_{\tilde{t}_1} = 360$ GeV, $m_{\tilde{u}_R} = 543$ GeV, $m_{\tilde{d}_R} = 539$ GeV, $m_{\tilde{u}_L} = 561$ GeV, $m_{\tilde{d}_L} = 566$ GeV]

Electroweak Contributions – photon-induced

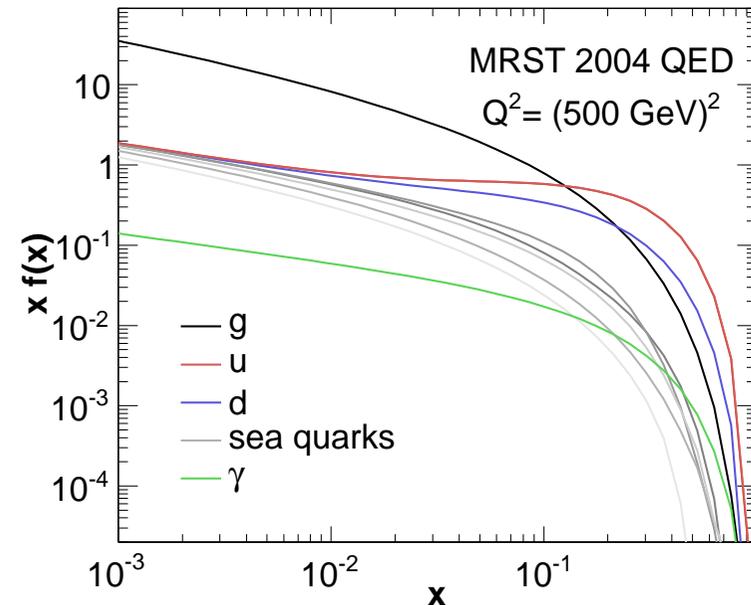
New production channel for $\tilde{g}\tilde{q}$, $\tilde{t}\tilde{t}^*$, and $\tilde{q}\tilde{q}^*$ production:

- $\mathcal{O}(\alpha_s\alpha)$: photon induced processes

[Hollik, Kollar, MT '07], [Hollik, Mirabella '08]
[Hollik, Mirabella, MT '08]



- not present at LO at the hadronic level
- **MRST 2004 QED**: inclusion of **NLO QED effects** in the evolution of PDFs
 - ➔ non-zero photon distribution
 - ➔ non-zero hadronic contributions

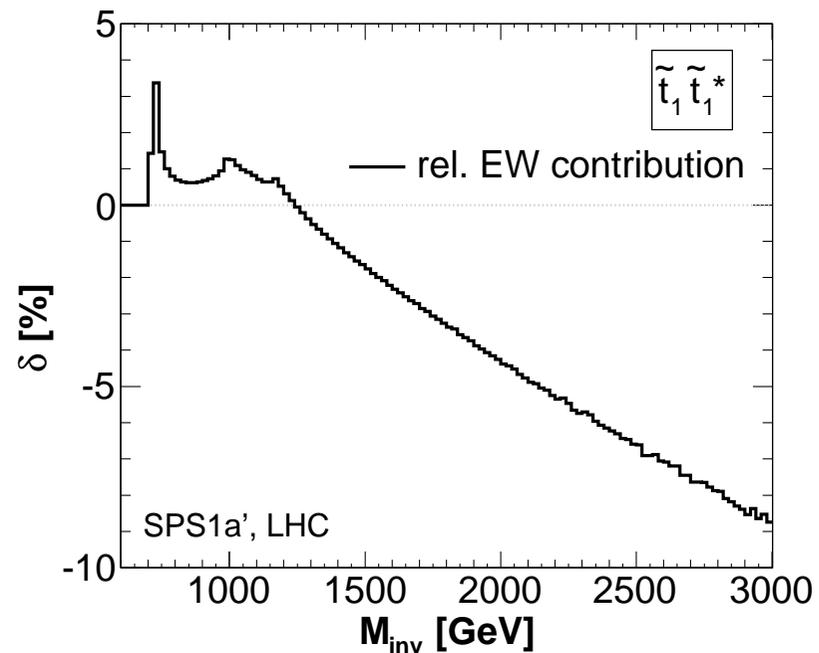
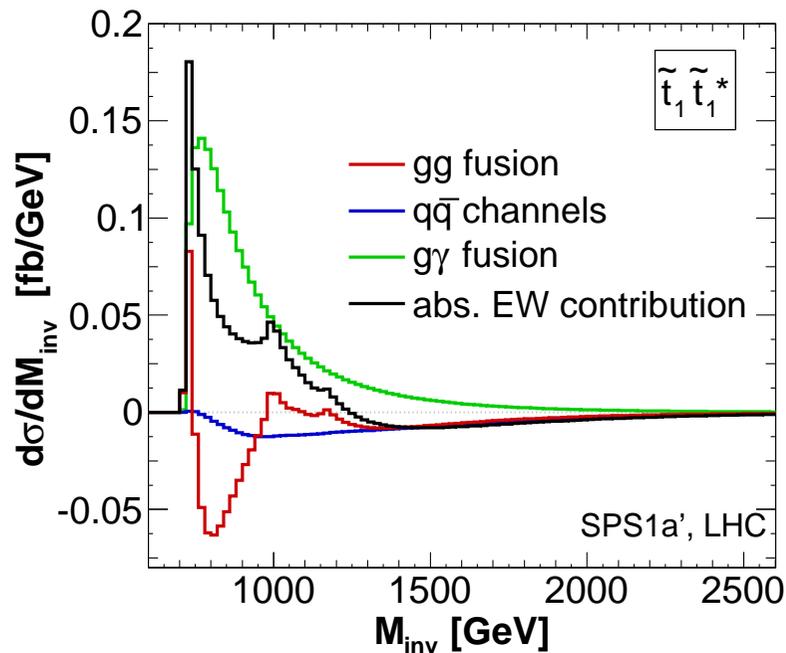


Numerical Results: Hadronic Cross Sections

$\tilde{t}_1 \tilde{t}_1^*$ prod.:

	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW, tree}$ $\mathcal{O}(\alpha^2)$	δ
$\tilde{t}_1 \tilde{t}_1^*$	2670 fb	-22 fb	38 fb	1.2 fb	0.6%

[SPS1a': typical mSUGRA scenario]
 $[m(\tilde{t}_1) = 360 \text{ GeV}, \text{MRST 2004 QED}, 14 \text{ TeV}]$

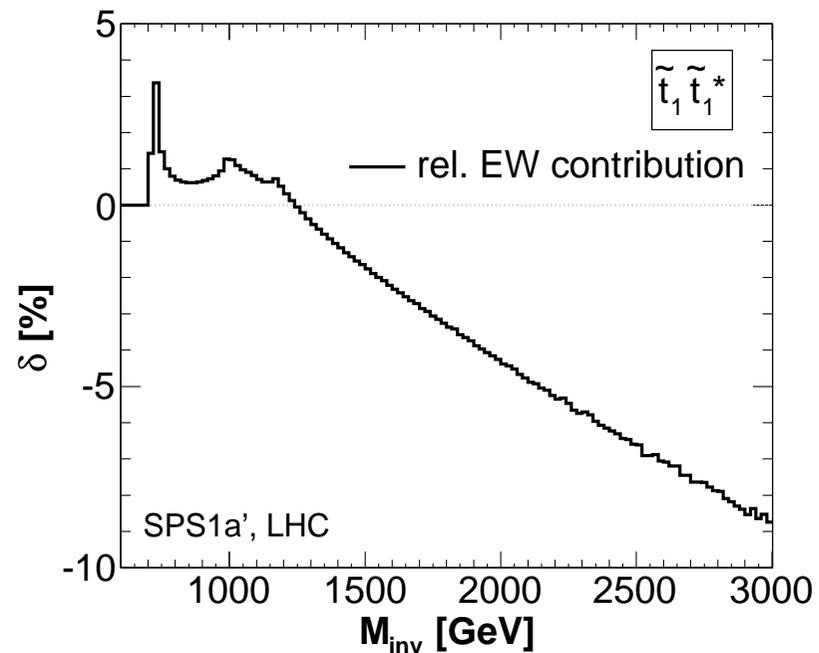
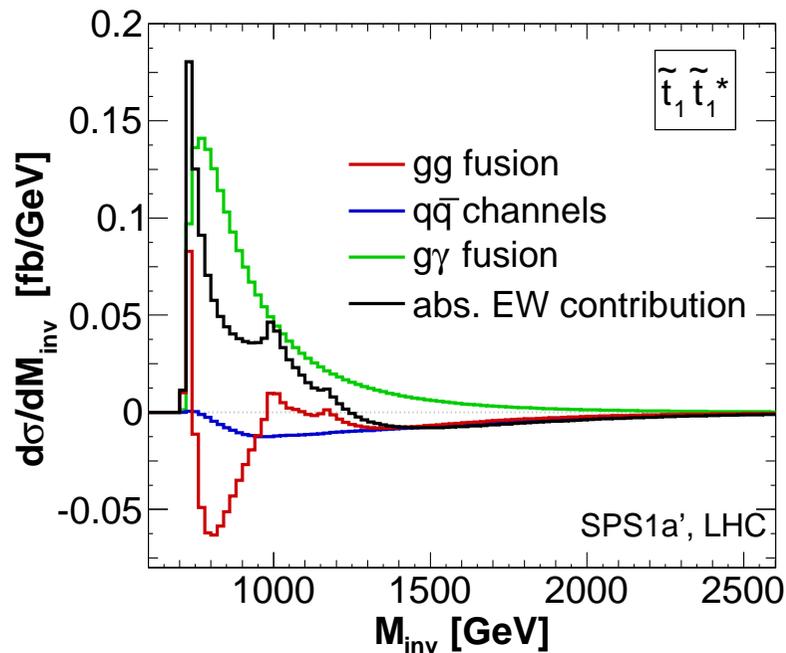


- **$g\gamma$ contributions** are of comparable size to NLO EW corrections!
- **EW contributions** grow up to $\sim 10\%$ for large values of M_{inv}

Numerical Results: Hadronic Cross Sections

$\tilde{t}_1 \tilde{t}_1^*$ prod.:

	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW, tree}$ $\mathcal{O}(\alpha^2)$	δ
14 TeV	2670 fb	-22 fb	38 fb	1.2 fb	0.6%
7 TeV	278 fb	-2.4 fb	5.5 fb	0.2 fb	1.2%



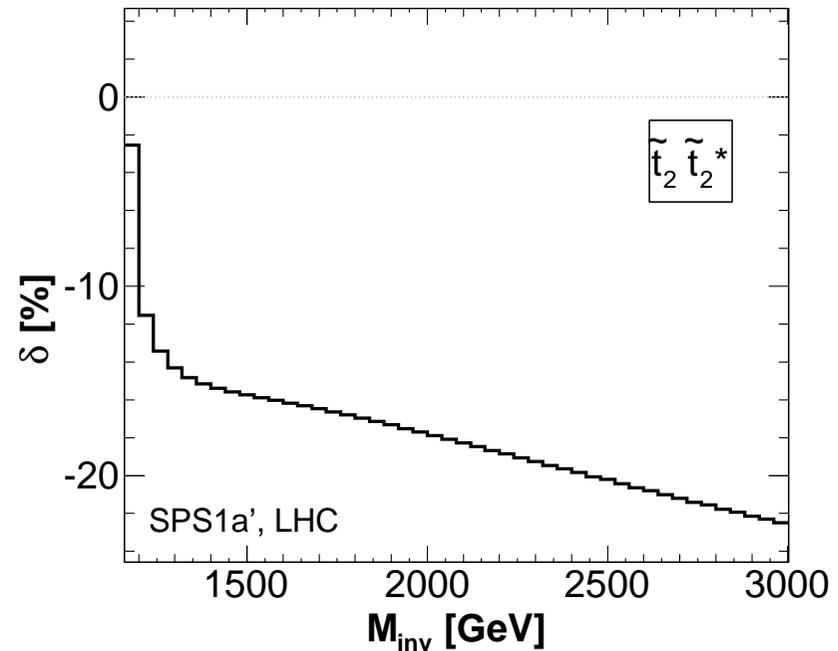
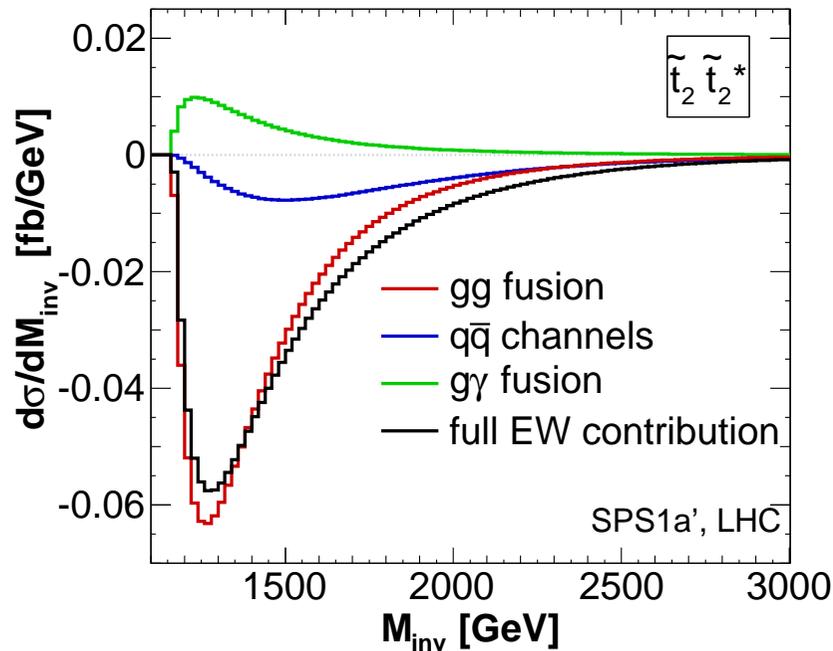
- **$g\gamma$ contributions** are of comparable size to NLO EW corrections!
- **EW contributions** grow up to $\sim 10\%$ for large values of M_{inv}

Numerical Results – $\tilde{t}_2\tilde{t}_2^*$ production

$\tilde{t}_2\tilde{t}_2^*$ prod.:

	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW,tree}$ $\mathcal{O}(\alpha^2)$	δ
$\tilde{t}_1\tilde{t}_1^*$	2670 fb	-22 fb	38 fb	1.2 fb	0.6%
$\tilde{t}_2\tilde{t}_2^*$	190 fb	-32 fb	3.8 fb	0.3 fb	-15%

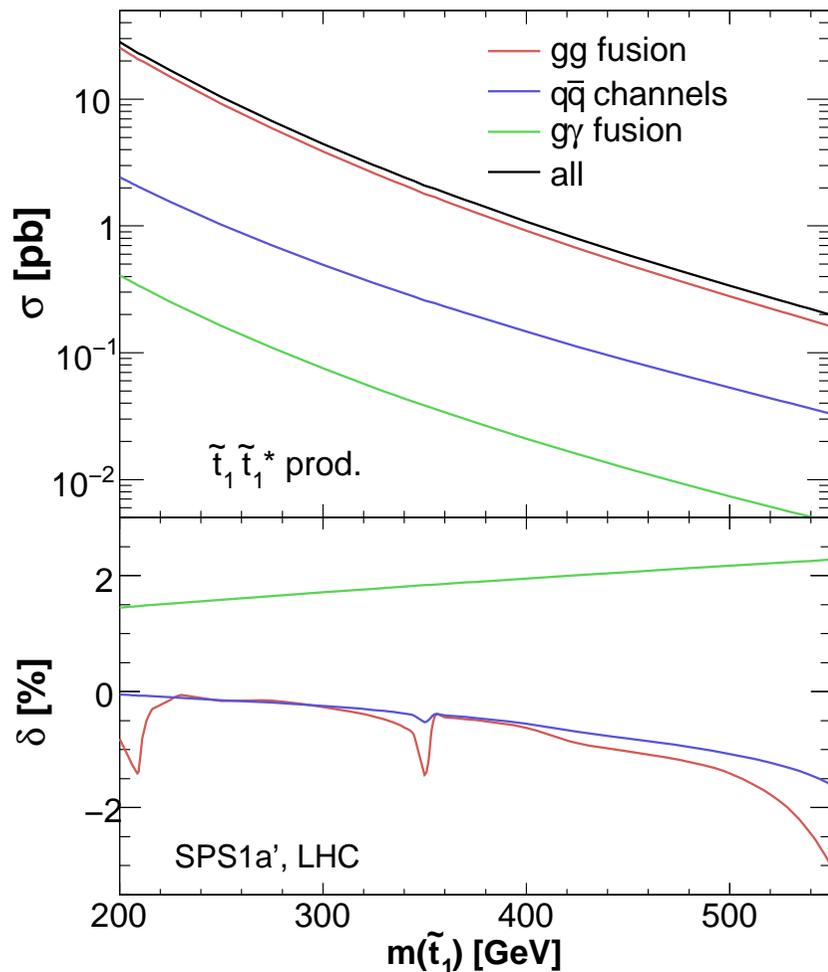
$[m(\tilde{t}_1) = 360 \text{ GeV}, m(\tilde{t}_2) = 580 \text{ GeV}, \text{MRST 2004 QED}, 14 \text{ TeV}]$



- integrated cross section suppressed from heavy \tilde{t}_2 -mass,
- but $\mathcal{O}(\alpha_s^2\alpha)$ **corrections enhanced** for more left-handed \tilde{t}_2

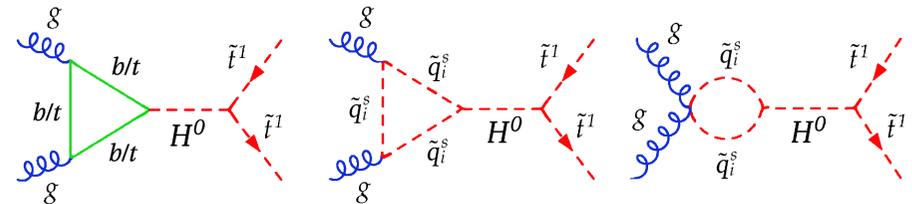
$\tilde{t}_1 \tilde{t}_1^*$ production: $m(\tilde{t}_1)$ dependence

- Relative corrections δ with respect to total born cross section ($gg + q\bar{q}$),

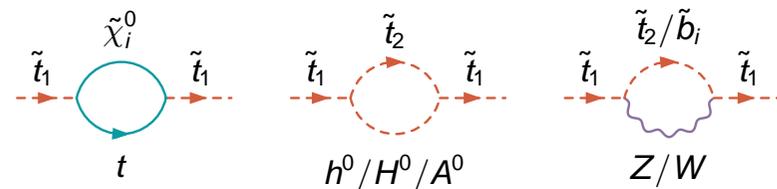


stop mass $m(\tilde{t}_1)$ **varied** around SPS 1a' value, all other parameters fixed

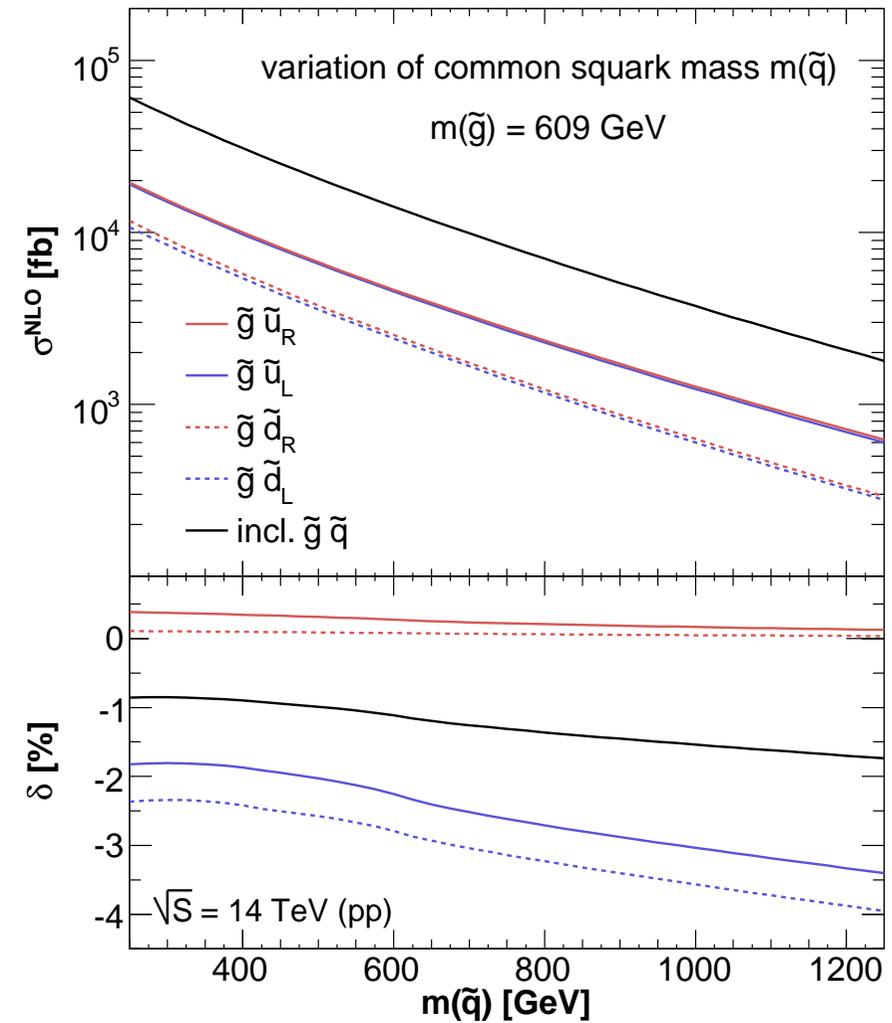
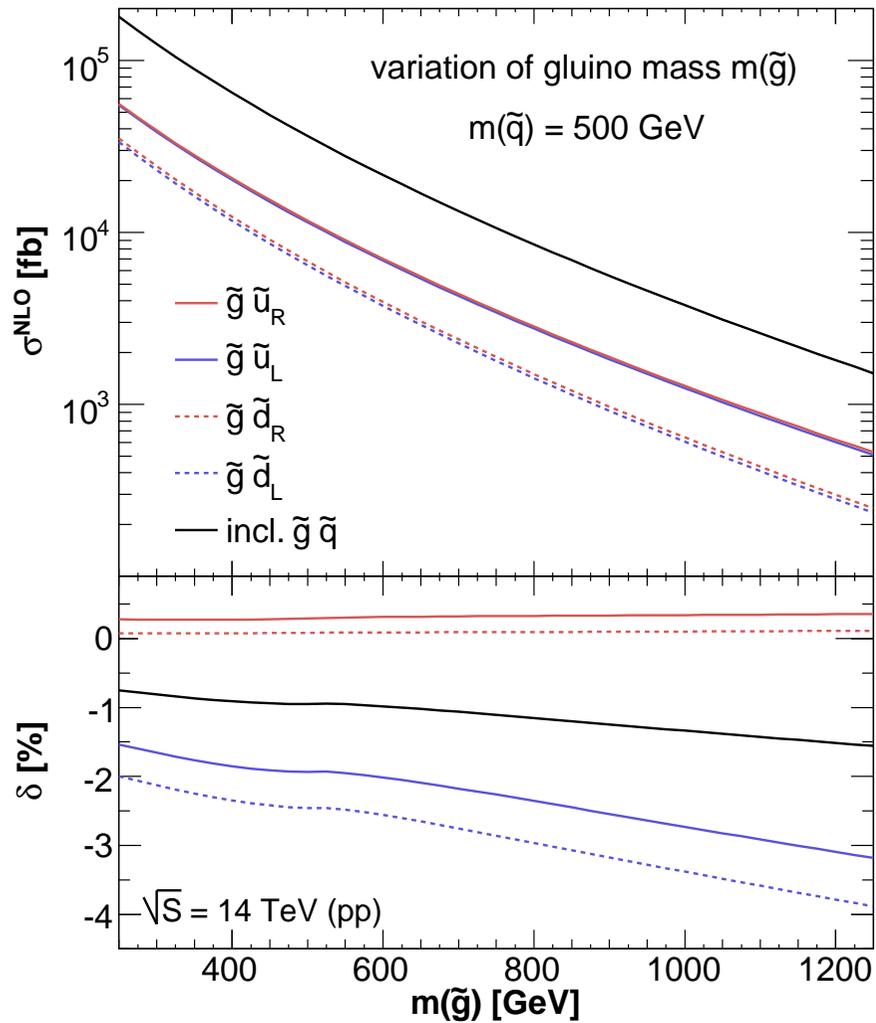
- moderate contributions, at percent level
- thresholds in H^0 diagrams



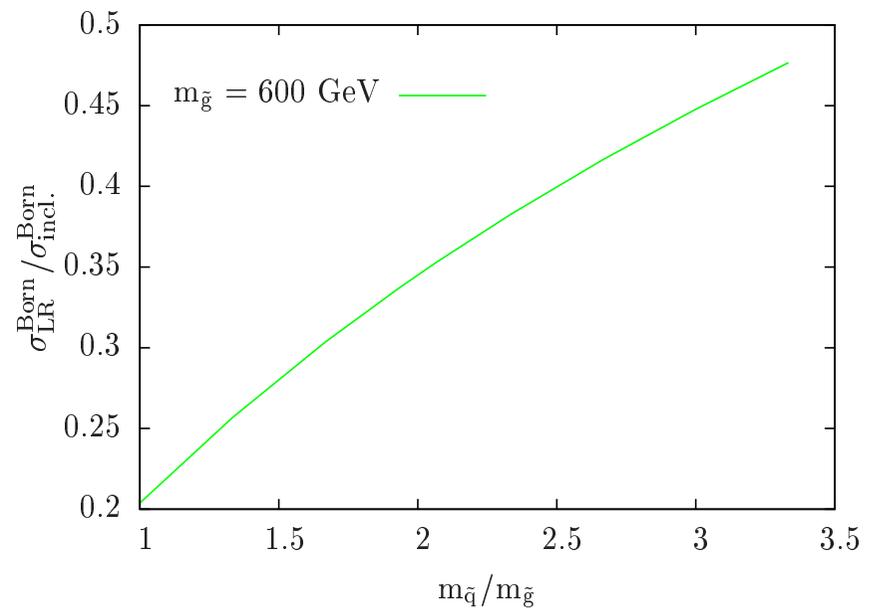
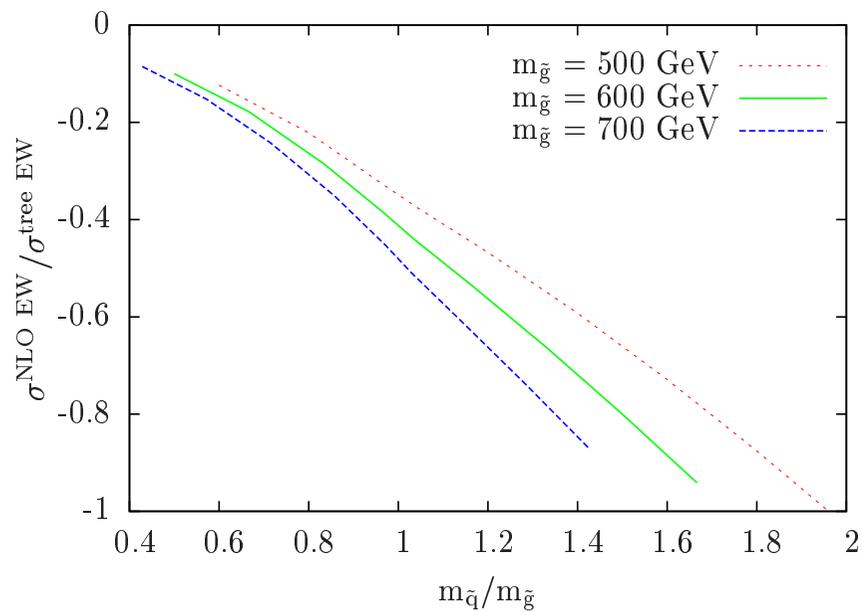
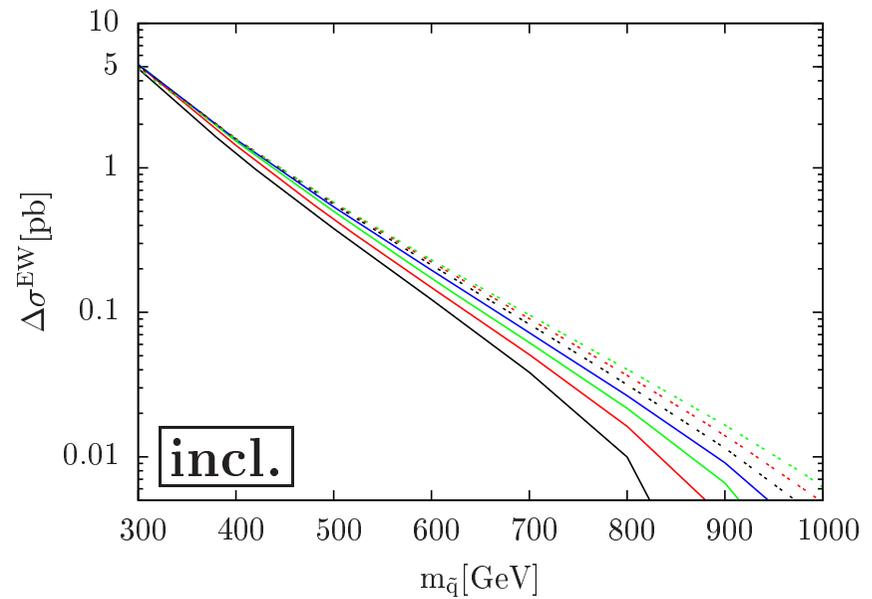
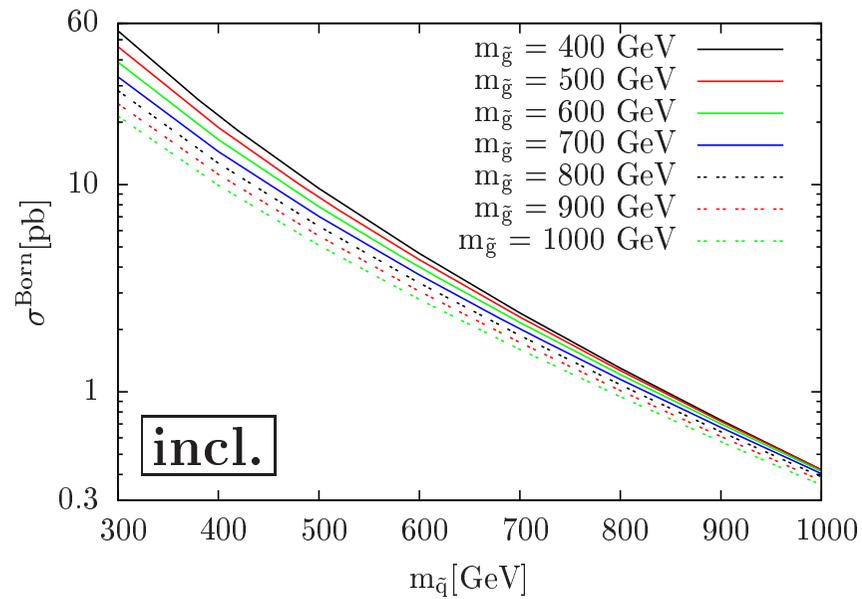
- thresholds in top-squark wave function renormalization



$\tilde{g}\tilde{q}$ production: $m_{\tilde{g}}, m_{\tilde{q}}$ dependence



$\tilde{q}\tilde{q}$ production: $m_{\tilde{q}}, m_{\tilde{g}}$ dependence



Squarks and Top-Squarks (Stops)

- $\tilde{q}_{L/R}$ SUSY **partners of quarks**, i.e.
- same quantum numbers as $q_{L/R}$, but **scalar particles**
- not yet observed, heavy particles
- **SUSY particles** of same color and charge **mix**:

$$\mathcal{L}_{\tilde{q}\tilde{q}} = -(\tilde{q}_L^*, \tilde{q}_R^*) \begin{pmatrix} m_q^2 + A_{LL} & m_q B_{LR} \\ m_q B_{LR} & m_q^2 + C_{RR} \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix} = -(\tilde{q}_1^*, \tilde{q}_2^*) \begin{pmatrix} m_{\tilde{q}_1}^2 & 0 \\ 0 & m_{\tilde{q}_2}^2 \end{pmatrix} \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix}$$

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_q & \sin \theta_q \\ -\sin \theta_q & \cos \theta_q \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}, \quad \begin{aligned} A_{LL} &= m_{\tilde{Q}}^2 - (I_q^3 - e_q \sin^2 \theta_W) m_Z^2 \cos 2\beta \\ B_{LR} &= A_q - \mu \tan^{\mp 1} \beta \\ C_{RR} &= m_{\tilde{U}/\tilde{D}}^2 + e_q \sin^2 \theta_W m_Z^2 \cos 2\beta \end{aligned}$$

$$m_{\tilde{q}_{1,2}}^2 = \frac{1}{2} \left(A_{LL} + C_{RR} \mp \sqrt{(A_{LL} - C_{RR})^2 + 4m_q^2 B_{LR}^2} \right); \quad \tan 2\theta_q = \frac{2m_q B_{LR}}{A_{LL} - C_{RR}}$$

Squarks and Top-Squarks (Stops)

- $\tilde{q}_{L/R}$ SUSY **partners of quarks**, i.e.
- same quantum numbers as $q_{L/R}$, but **scalar particles**
- not yet observed, heavy particles
- **SUSY particles** of same color and charge **mix**:

$$\mathcal{L}_{\tilde{q}\tilde{q}} = -(\tilde{q}_L^*, \tilde{q}_R^*) \begin{pmatrix} m_q^2 + A_{LL} & m_q B_{LR} \\ m_q B_{LR} & m_q^2 + C_{RR} \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix} = -(\tilde{q}_1^*, \tilde{q}_2^*) \begin{pmatrix} m_{\tilde{q}_1}^2 & 0 \\ 0 & m_{\tilde{q}_2}^2 \end{pmatrix} \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix}$$

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_q & \sin \theta_q \\ -\sin \theta_q & \cos \theta_q \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix},$$

$$m_{\tilde{q}_{1,2}}^2 = \frac{1}{2} \left(A_{LL} + C_{RR} \mp \sqrt{(A_{LL} - C_{RR})^2 + 4m_q^2 B_{LR}^2} \right)$$

- large top-Yukawa coupling:
 - **mixing** is important for stops!
 - **RGE's**: stops lighter than first gen. squark
 - \tilde{t}_1 **lightest squark** in many SUSY models!

